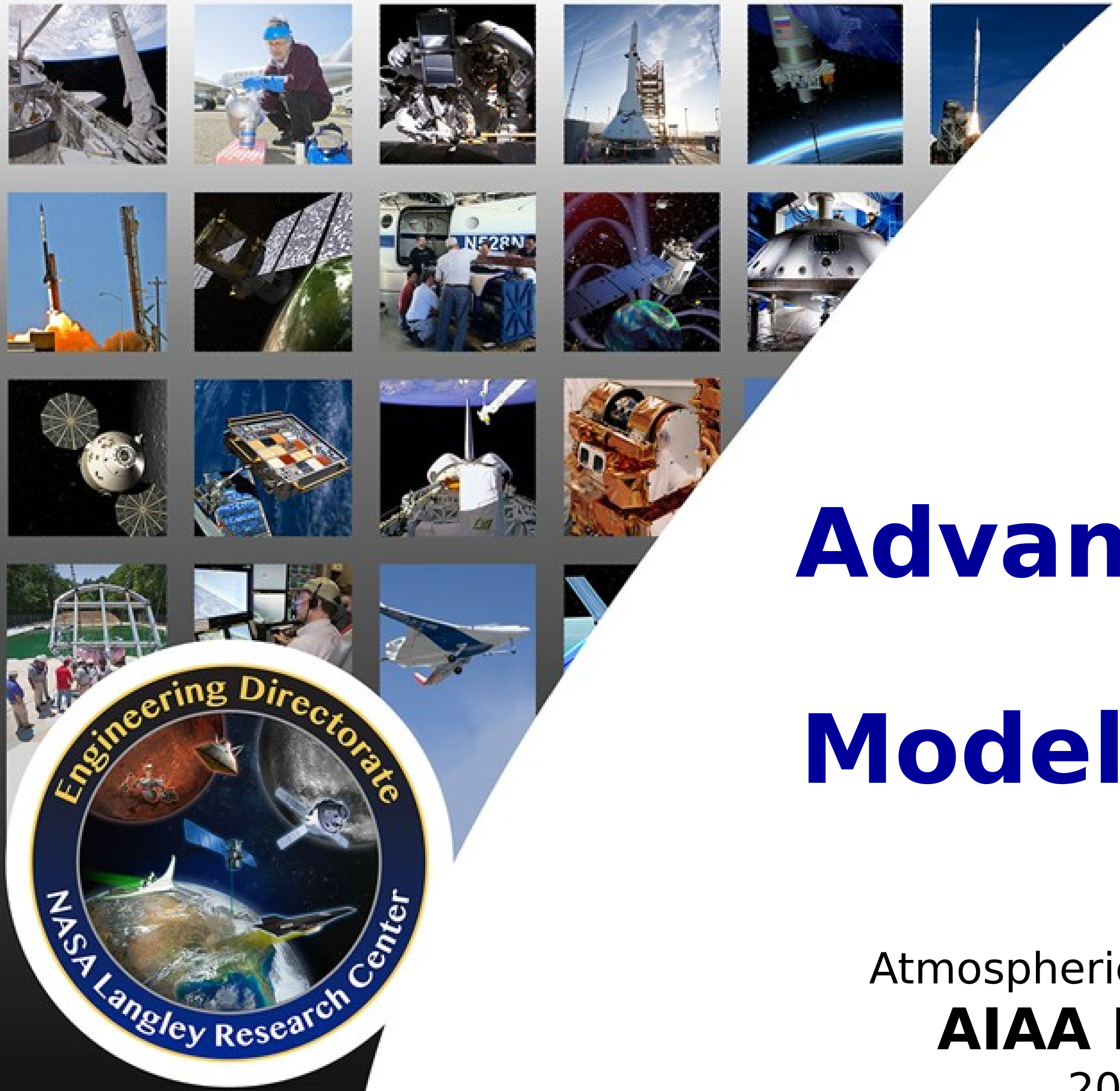
National Aeronautics and
Space Administration



Advances in EDL Flight Mechanics Modeling & Simulation

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AIAA Hampton Roads Section
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Background

- **During Mars Pathfinder development (1995-7), a team at LaRC was assembled to help design, simulate, and assess performance of integrated EDL systems**
  - It was understood that the vehicle, trajectory, GN&C, and aerodynamics were closely coupled
  - Significant differences from Viking (1976) and resulting concerns led to the integration of models from multiple disciplines into a single simulation framework (POST) JSR Vol 32, No. 6
  - This approach blends flight mechanics/GN&C, aerosciences, and systems engineers as a cohesive, multidisciplinary unit
- **This type of end-to-end integrated performance analysis can provide enhanced insight and understanding of increasingly complicated flight systems**
  - Monte Carlo statistical analysis, system faults, off-nominal/abort scenarios, "what if?"
    - We don't just look at a single flight phase, we don't just look at the nominal
  - Historically, this has been computationally expensive
    - Improvements in compute systems, hardware, and simulation software improves runtime, possible level of fidelity
    - How do we take advantage of that and maintain flight-validated heritage?
- **But first…**

Flight Mechanics Modeling & Simulation

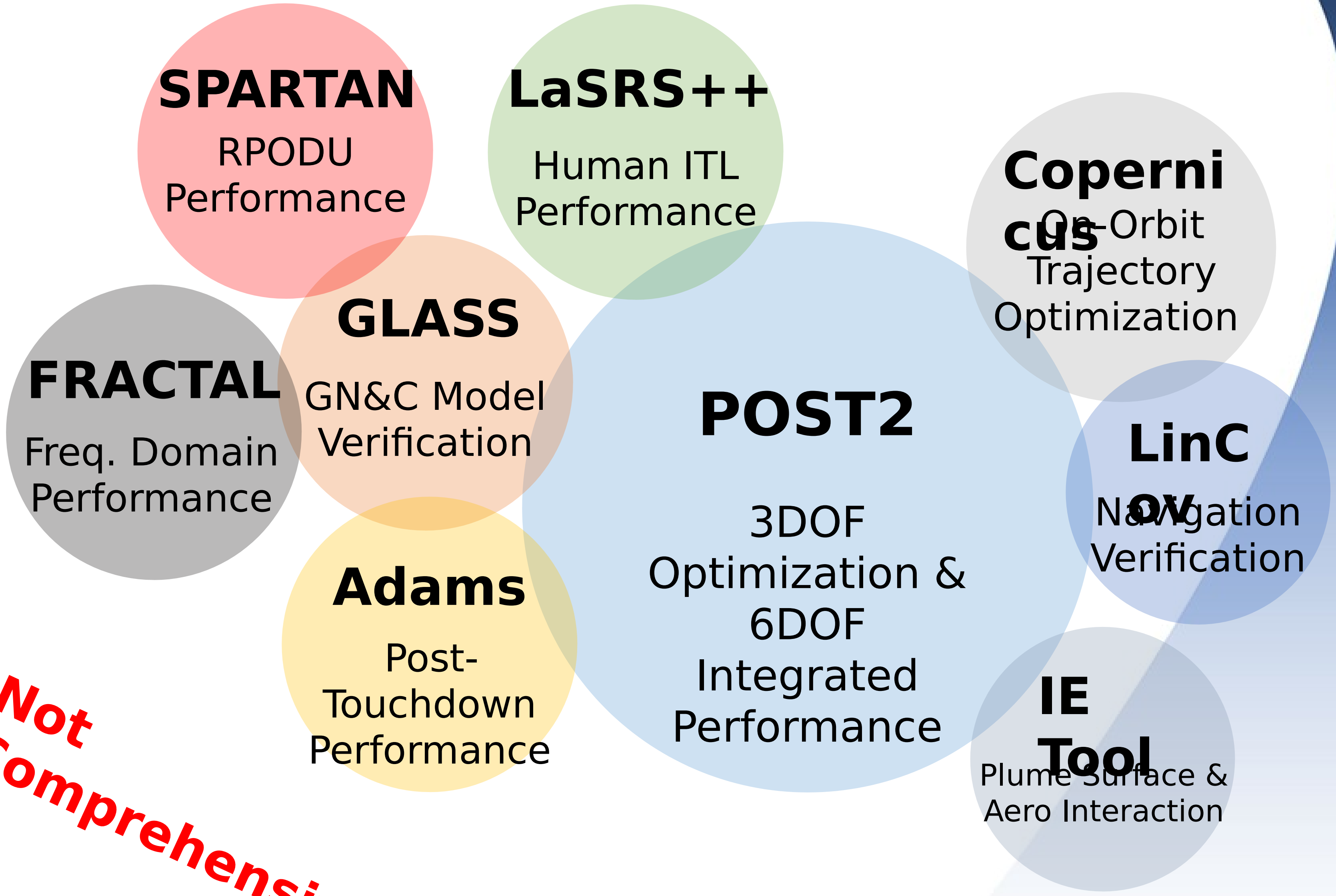
- **What does this mean? Different groups have different definitions!**
  - 3DOF? 6DOF? Flight dynamics? Trajectory optimization? GN&C?
- **Ultimately, "flight mechanics" is a very broad field that can include elements from other disciplines**
- **For the purposes of this talk, flight mechanics is the study of the performance of the integrated "system of systems" that make up a flight vehicle and its environment**
  - 3/6/Multi-DOF equations of motion
  - Trajectory optimization
  - Guidance, navigation, & control
  - Aerodynamics
  - Atmosphere & environments
  - Mass & structures
  - Propulsion
  - Manual control effects
  - Off-nominal and abort scenarios
  - …

Not Comprehensive!

- **Many simulation environments or tools exist that can assess elements of flight mechanics**
  - Copernicus, DSENDS, Genesis, STK, QuickShot, OTIS, …

Example: Human Landing Systems (HLS) NASA Insight: DDL

- **Many different simulation environments from different disciplines work in tandem**
  - Overlap indicates shared data, handoffs, or analyses
- **Some tools focus on specific phases**
- **We are going to focus on one tool**



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Program to Optimized Simulated Trajectories II

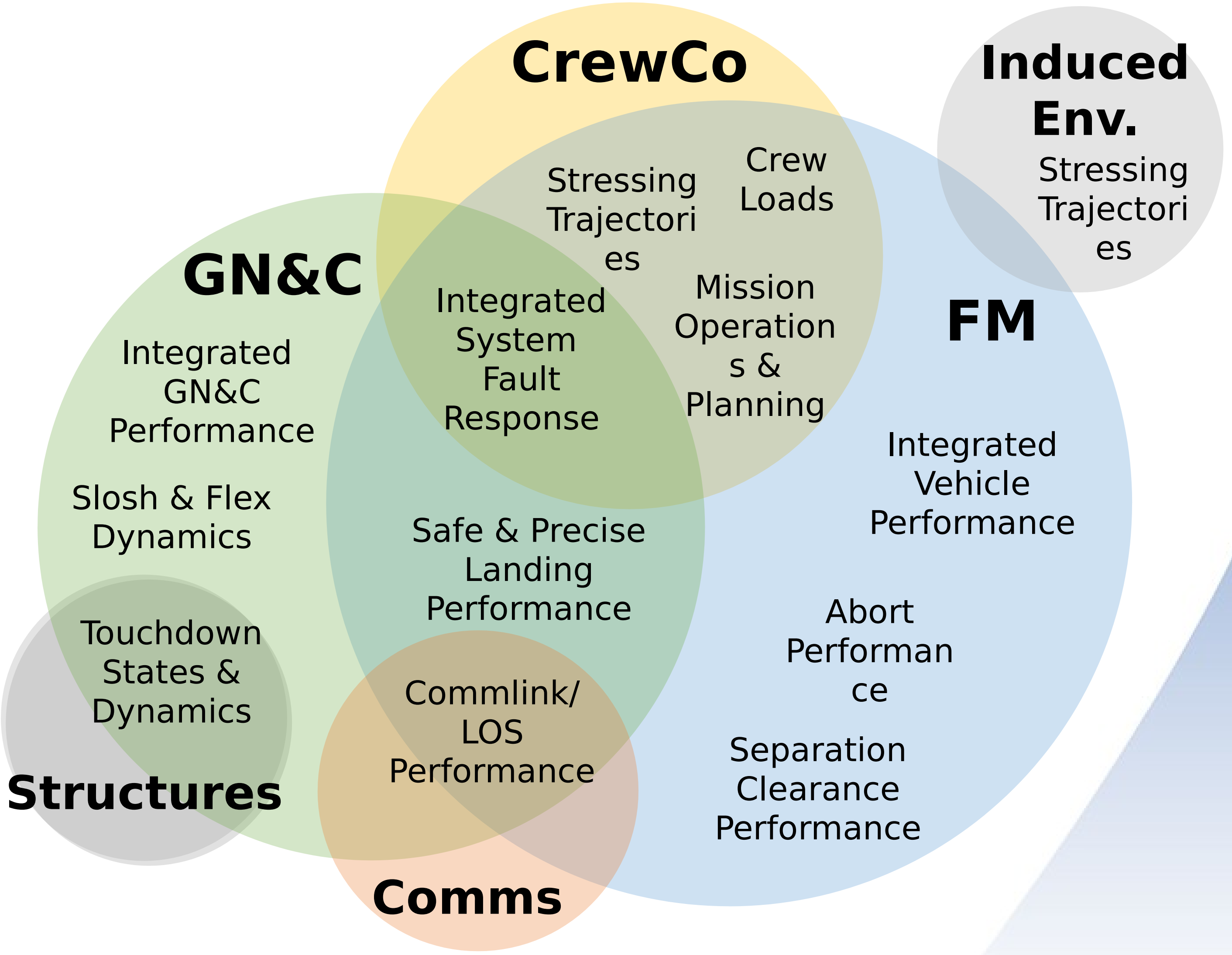
(POST2)

What is POST2?

- **Flight-validated, generalized, event-based, point-mass vehicle & trajectory simulation codebase**
  - 3/6/Multi-DOF
  - Continuously developed and maintained in-house at Langley Research Center
  - “Developers-as-Users”
- **Key Features**
  - “Input deck”-based setup with custom, robust input language
  - Interfaces with user-provided multidisciplinary engineering models and flight software
  - Built-in trajectory optimization
  - API permits external tools (e.g. Copernicus) to call POST2 and optimize on it directly (new for 2023!)
- **Key Applications**
  - Statistical analysis of end-to-end integrated performance
  - Orbital & atmospheric trajectory optimization & design
  - GN&C algorithm development & assessment
  - Off-nominal, faults, aborts, and margin analysis

Sample POST2 Simulation Products (HLS)

- **POST2 simulation products are cross-disciplinary**
  - Thus, simulation developers/analysts must also have sufficient knowledge of these disciplines
- **Ownership of all inputs and outputs is key**
  - No finger-pointing or “because the algorithm said so”
  - “Vertical Integration” of software development **and** flight mechanics analysis



Vertical Integration

- **Engineering/support tools may often be viewed as "black boxes"**
  - You don't see the code, you don't compile it, you don't debug it
  - If something goes wrong, you contact the software developer
- **POST2/D205 does not follow this model**
  - We write the code, we compile it, we use it
  - Use of external libraries is avoided when possible
  - If something goes wrong, we are the developers!
- **For delivered code/modules (e.g., flight software), we work closely with model authors to verify implementation**

Design
- New features proposed and discussed at Development Team meetings
- Address bug fixes, maintenance issues, etc.

Implementation
- Prototypes developed by aerospace engineers
- Production versions implemented by software engineers

Testing
- Continuous unit & regression testing
- Project-level testing (changes regressed against all active POST2-driven flight projects)

Distribution
- Internal versions include in-development engineering models
- External versions are packaged for release nasa.gov/post2

Analysis
- Flight projects, flight tests, ground tests, proposals, research, …

State of the POST2 Codebase

- **Versions have been used to support Shuttle, all NASA Mars EDL systems (except Viking), SLS, CCP, HLS/Artemis, numerous ground/flight tests …**
  - The current version (4.x) is slimmer, cleaner, more modular, more robust, and more flexible than any previous version
  - Versions are maintained for distribution to other NASA centers, DOD, industry, and academia
- **But… it is based on Shuttle-heritage Fortran code from the 1970s**
  - Programming standards computer hardware paradigms have changed
  - Previous upgrade work has included updating all code to C/C++ and adopting a unified development system
  - Current efforts (2020+) are focused on updating the POST2 codebase to take advantage of more modern software and hardware, including **flexible APIs** and **multi-threaded systems**

Year	Type	Project	Phase	Planet	Discipline	Title
1988	Tech Memo	AFE	Aerobraking	Earth	FM	Aeroassist Flight Experiment Guidance (Quiet Time)
1995	Journal Article	Pathfinder	EDL	Mars	FM	Mars Pathfinder Six-Degree-of-Freedom Entry Analysis
1996	Conference Paper	METEOR	EDL	Earth	FM	Six Degree-of-Freedom Entry Dispersion Analysis for the METEOR Recovery Module
1998	Conference Paper	Mars Surveyor	EDL	Mars	GN&C	An Atmospheric Guidance Algorithm Testbed for the Mars Surveyor Program 2001 Orbiter and Lander
1998	Conference Paper	Mars Surveyor	EDL	Mars	GN&C	Numerical roll reversal predictor corrector aerocapture and precision landing guidance algorithms for the Mars Surveyor Program 2001 missions
1999	Conference Paper	MSP '01	Aerocapture	Mars	GNC/FM	Martian Aerocapture Terminal Point Guidance: A Reference Path Optimization Study
2002	Conference Paper	Odyssey	Aerobraking	Mars	FM	The Development and Evaluation of an Operational Aerobraking Strategy for the Mars 2001 Odyssey Orbiter
2002	Conference Paper	MSL	EDL	Mars	FM	Mars Smart Lander Simulations For Entry, Descent, And Landing
2005	Conference Paper	MRO	Aerobraking	Mars	FM	NASA Langley Trajectory Simulation Capabilities for Mars Reconnaissance Orbiter
2005	Conference Paper	Huygens	EDL	Titan	FM/Aerothermal	Prediction of the Aerothermodynamic Environment of the Huygens Probe
2006	Journal Article	MER	EDL	Mars	FM	Mars Exploration Rover Six-Degree-of-Freedom Entry Trajectory Analysis
2006	Journal Article	MSL	EDL	Mars	FM	Mars Science Laboratory Simulations for Entry, Descent, and Landing
2007	Conference Paper	MRO	Aerobraking	Mars	FM	Mars Reconnaissance Orbiter Operational Aerobraking Phase Assessment
2007	Conference Paper	ALHAT	DDL	Moon	FM/ Nav	POST2 End-To-End Descent and Landing Simulation for the Autonomous Landing and Hazard Avoidance Technology Project
2007	Conference Paper	MRO	Aerobraking	Mars	FM	Mars Reconnaissance Orbiter Operational Aerobraking Phase Assessment
2007	Conference Paper	Huygens	EDL	Titan	FM	Huygens Titan Probe Trajectory Reconstruction Using Traditional Methods and the Program to Optimize Simulated Trajectories II
2008	Conference Paper	Mars Phoenix	EDL	Mars	FM	Mars Phoenix Entry, Descent, and Landing Simulation Design and Modeling Analysis
2008	Conference Paper	ALHAT	DDL	Moon	[illegible]M/GNC	Advances in POST2 End-to-End Descent and Landing Simulation for the ALHAT Project
2009	Conference Paper	Mars Phoenix	EDL	Mars	[illegible]M	Entry, Descent, and Landing Operations Analysis for the Mars Phoenix Lander
2009	NASA Tech Memo	Huygens	EDL	Titan	[illegible]	Cassini/Huygens Probe Entry, Descent, And Landing (Edl) At Titan Independent Technical Assessment
2010	Conference Paper	ALHAT	DDL	Moo[illegible]	GNC/FM	POST2 End-to-End Descent and Landing Simulation for ALHAT Design Analysis Cycle 2
2011	Conference Paper	LAS	Ascent	Earth	[illegible]	Reverse Launch Abort System Parachute Architecture Trade Study
2011	Journal Article	Phoenix	EDL	Mars	[illegible]M	Entry, Descent, and Landing Performance of the Mars Phoenix Lander
2011	Conference Paper	AutoAB	Aerobraking	Mars	FM/GNC	[illegible]tation and Simulation Results Using Autonomous Aerobraking Development Software
2012	Conference Paper	AutoAB	Aerobraking	Mars/Venus/Titan	FM/GNC	Auto[illegible]mou[illegible]bra[illegible]ng Development Software: Phase One Performance Analysis At Mars, Venus, And Titan
2012	Conference Paper	MSL	EDL	Mars	FM	Ground Conta[illegible]el F[illegible] Mars Science Laboratory Mission Simulations
2013	Conference Paper	MSL	EDL	Mars	FM	Assessment of the Mars Sc[illegible]tory Entry, Descent, and Landing Simulation
2013	Conference Paper	IRVE-3	EDL	Earth	Reconstruction	IRVE-3 Post-Flight Reconstruction
2015	Conference Paper	LDSD	EDL	Earth	FM	Supersonic Flight Dynamics Test 1 – Post-fli[illegible]ent of Simulation Performance
2015	Conference Paper	LDSD	EDL	Earth	FM	LDSD POST2 Simulation and SFDT-1 Pre-Flight Launch [illegible]s
2015	Conference Paper	LDSD	EDL	Earth	FM	SFDT-1 Camera Pointing and Sun-Exposure Analysis and Flight Perfor[illegible]ance
2016	Conference Paper	LDSD	EDL	Earth	FM	Post-Flight Assessment of Low Density Supersonic Decelerator Flight Dynamics Test 2 Simulation
2017	Conference Paper	SLS	Ascent	Earth	FM	Launch Vehicle Ascent Trajectory Simulation Using the Program to Optimize Simulated Trajectories II
2017	Conference Paper	Exo-Brake	EDL	Earth	FM	Guidance Scheme for Modulation of Drag Devices to Enable Return from Low Earth Orbit
2019	Conference Paper	Humans2Mars	EDL	Mars	GN&C	Integrated Flush Air Data Sensing System Modeling for Planetary Entry Guidance with Direct Force Control
2019	Conference Paper	ADEPT	EDL	Earth	FM	Flight Mechanics Modeling and Post-Flight Analysis of ADEPT SR-1
2020	Conference Paper	Humans2Mars	EDL	Mars	GN&C	Overview of a Generalized Numerical Predictor-Corrector Targeting Guidance with Application to Human-Scale Mars Entry, Descent, and Landing
2020	Conference Paper	Humans2Mars	EDL	Mars	GN&C	Low Lift-to-Drag Morphing Shape Design
2020	Journal Article	NepCap	Aerocapture	Neptune	FM	Investigation of direct force control for aerocapture at Neptune
2021	Tech Memo	MER	EDL	Mars	Reconstruction	Mars Exploration Rovers EDL Trajectory and Atmosphere Reconstruction using NewSTEP
2022	Conference Paper	Humans2Mars	EDL	Mars	GN&C	Integrated Precision Landing Performance and Technology Assessments of a Human-Scale Mars Lander Using a Generalized Simulation Framework
2022	Conference Paper	Artemis	DDL	Moon	GN&C	Precision Landing Performance of a Human-Scale Lunar Lander Using a Generalized Simulation Framework
2022	Journal Article	NepCap	Aerocapture	Neptune	FM	Flight control methodologies for Neptune aerocapture trajectories
2022	Conference Paper	SmallSat	Aerocapture	Earth/Mars/Venus	FM	Small Satellite-Sized Hypersonic Inflatable Aerodynamic Decelerators for Interplanetary Science Missions
2022	Conference Paper	SmallSat	Aerocapture	Earth/Mars/Venus	FM	Flight Envelope Assessment of SmallSat Aerocapture Trajectories at Venus and Mars

Not Comprehensive!

Thread Safety Updates

To be Presented at AIAA SciTech 2023, Anthony Williams

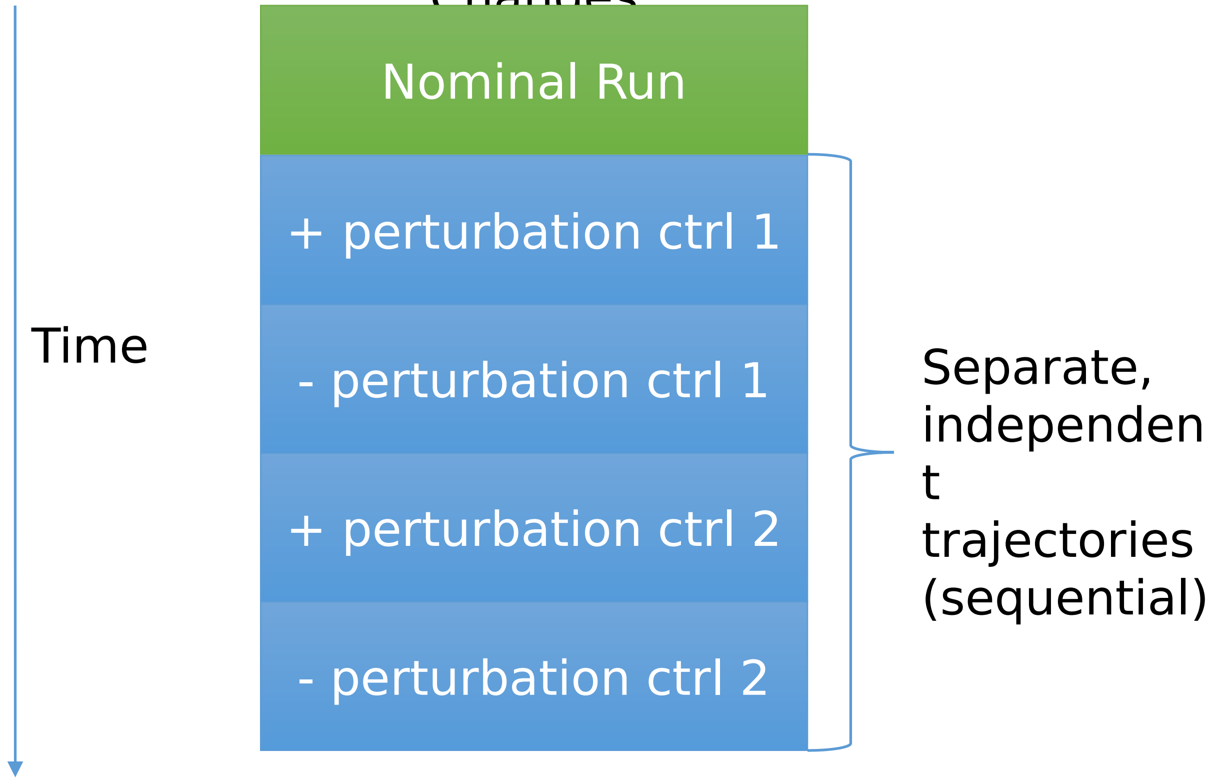
Thread Safety Overview

- **High-Performance Computing (HPC) is a rapidly developing hardware field, and can:**
  - Accelerate development and implementation of state-of-the-art GN&C
  - Accelerate implementation of optimization algorithms
  - Enables interoperability with external applications that also utilize HPCs
- **Previously, POST2 could not take advantage of HPC systems because it was not thread-safe**
  - Software is thread-safe if multiple threads perform calculations concurrently, and the output is not adversely affected
  - POST2 was structured such that the program, vehicle(s), and trajectory(ies) share global memory addresses
  - So, POST2 has been re-architected to encapsulate these memory structures, such that they do not share memory addresses

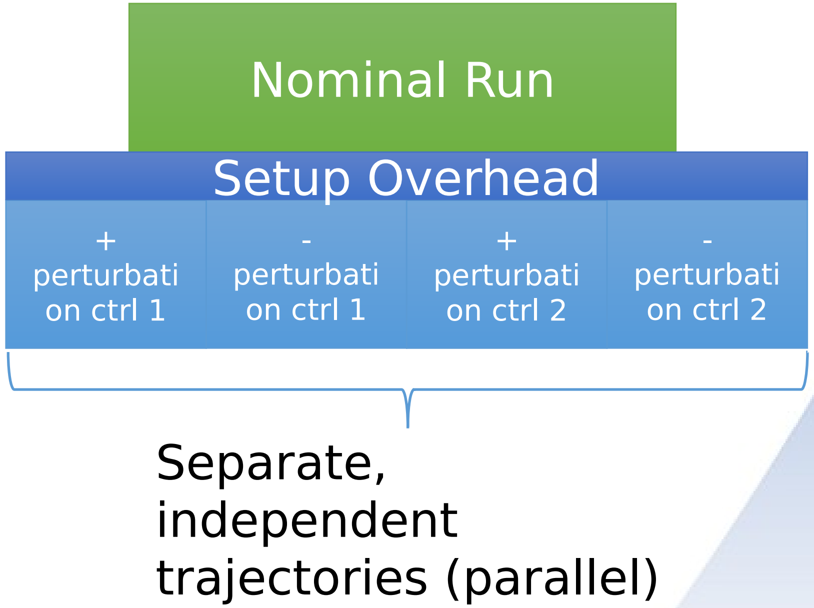
Parallel Optimization Framework (OpenMP)

- **Default optimization scheme in POST2 is the projected gradient method**
- **Multiple derivatives are needed to build a sensitivity or Jacobian matrix**
  - Controls for the optimization problem determine derivatives needed
- **Derivatives approximated via finite differencing**
  - Depending on type, i.e. central 2nd order, the number of trajectories needed changes

Before Thread-Safe Changes



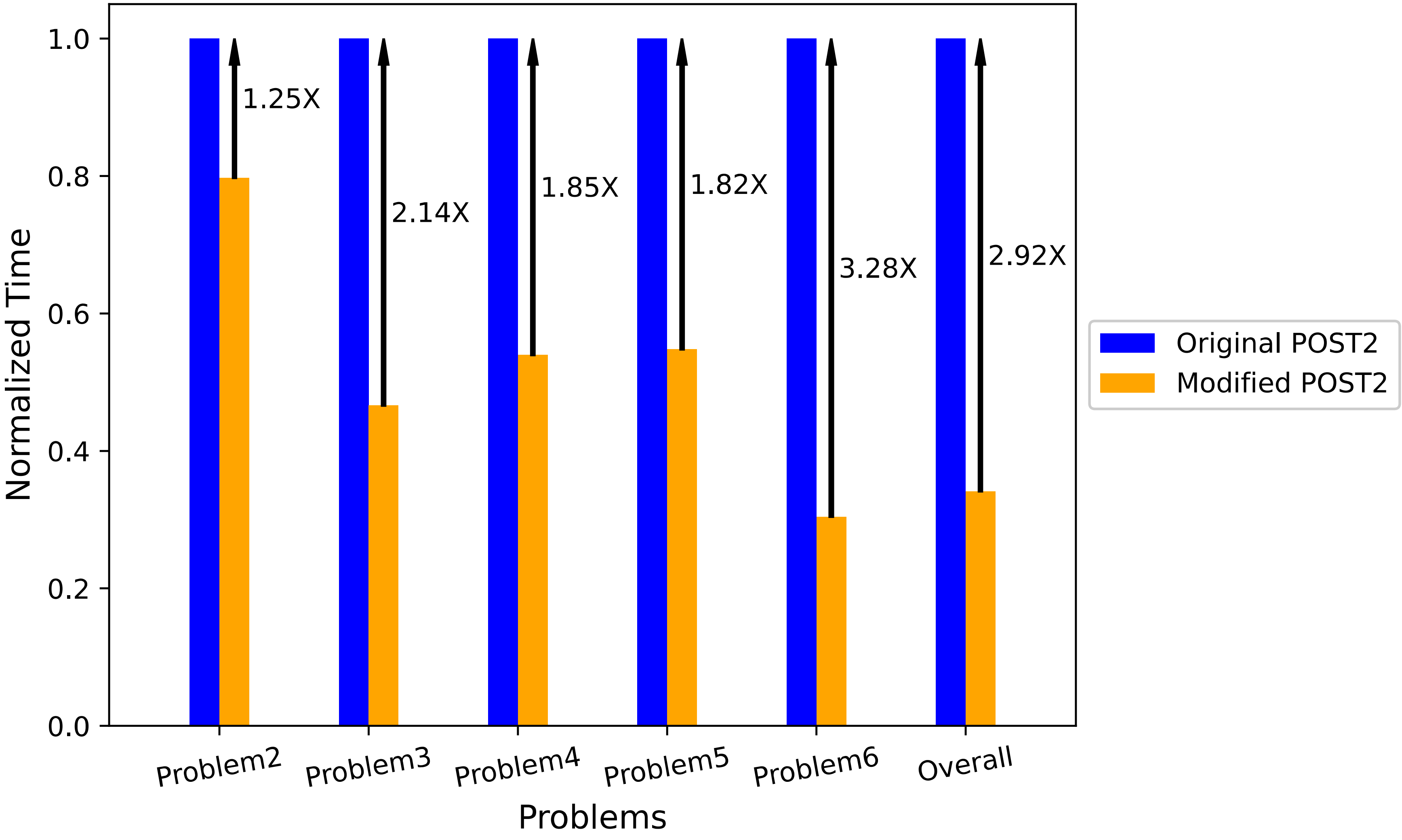
Thread-Safe Changes Made



Can achieve *up to* 2n times speed up for Jacobian calculation, where n is the**

Lunar Lander Trajectory Overall Time

Lower is Better



API Updates

API Overview

- **POST2 is a powerful “all-in-one” flight mechanics, trajectory design, trajectory optimization, and GN&C design tool**
  - Other tools are better-suited to long-period phases of flight (e.g., interplanetary transfers)
  - What if we could use POST2 as the dynamics driver for more complex phases of flight (e.g, EDL, ascent) and seamlessly link with other tools?
- **Solution: Application Programming Interface (API)**
  - Recent POST2 development has focused on creating API that will permit POST2 to be called directly by external programs, with no write-to-disk penalties
  - Data may now be passed directly between external apps and POST2 via memory, as opposed to writing out to disk
  - Current external applications/languages that have been tested to call POST2 include MATLAB, Python, and Copernicus
  - This could not have been accomplished without making POST2 thread-safe!

API Example: MATLAB

- **Used regression test from POST2 Core testing suite**
- **Wrote MATLAB script to perform same optimization problem as regression test, using MATLAB's fmincon()**
  - MATLAB calls POST2 API and retur optimization updates to console
  - Interface script still in developmer

```
function [objective,ineqCon,eqCon] = computeObjAndCon(indVals)

    % No inequality constraints for this problem
    ineqCon = [];

    % Independent variable names and events to perturb them
    indNames = {['dbank',0] ,['dbank',0] ,['dbank',0] ,['value',0]};
    events = [60., 70., 75., 60.];

    % Setting all independent variables
    for ii = 1:length(indNames)
        calllib('libpost2', 'post2_set_value', indNames{ii}, 1, events(ii), 1, indVals(ii));
    end

    % Running POST2
    calllib('libpost2','post2_run');

    % Gather outputs
    output = calllib('libpost2', 'post2_get_outputs');
    outputmat = get(output, 'Value');

    % Set data type for `data` pointer in the POST2_OUTPUT struct to be a
    % double pointer, that is a 1x(numOutputs*numTimesteps) array (housing numOutputs*numTimesteps doubles)
    setdatatype(outputmat.data,'doublePtr',1,outputmat.num_outputs*outputmat.num_timesteps);
    data = get(outputmat.data, 'Value');

    % The constraint for the problem is crrng + 1200
    crrng = data(end-1);
    eqCon = crrng + 1200;

    % Objective function is timrf1
    objective = calllib('libpost2','post2_get_value_at_event', output, 60.0, ['timrf1' 0]);

end
```

```
Independent:     Values                      Variables    Phases
 INDVAL( 1) =  1.89586779673034407e+01;      dbank       60.000
 INDVAL( 2) = -1.01877710713159146e+01;      dbank       70.000
 INDVAL( 3) = -2.55638927034625674e+00;      dbank       75.000
 INDVAL( 4) =  1.27898578754355853e+02;      critr       60.000

Targeting Errors:          Weighted Errors          Dep Variables   Phases
 e( 1) = -8.66310506e-05   we( 1) = -1.73262101e-05    crrng        100.000
 [crrng    -1.20000009e+03, targeting -1.200e+03]

 optvar =      timrf1
 optphs =      60.000
 optval =  1.27898579e+02

*** PROBLEM SOLVED ***
```

POST 2

```
indvals =

     1.934160909130076e+01    -1.035727438270013e+01    -2.334754111352773e+00    1.278993369296583e+02


targetErrors =

     6.821210263296962e-13


crrng =

    -1.199999999999999e+03


optval =

     1.278993369296586e+02
```

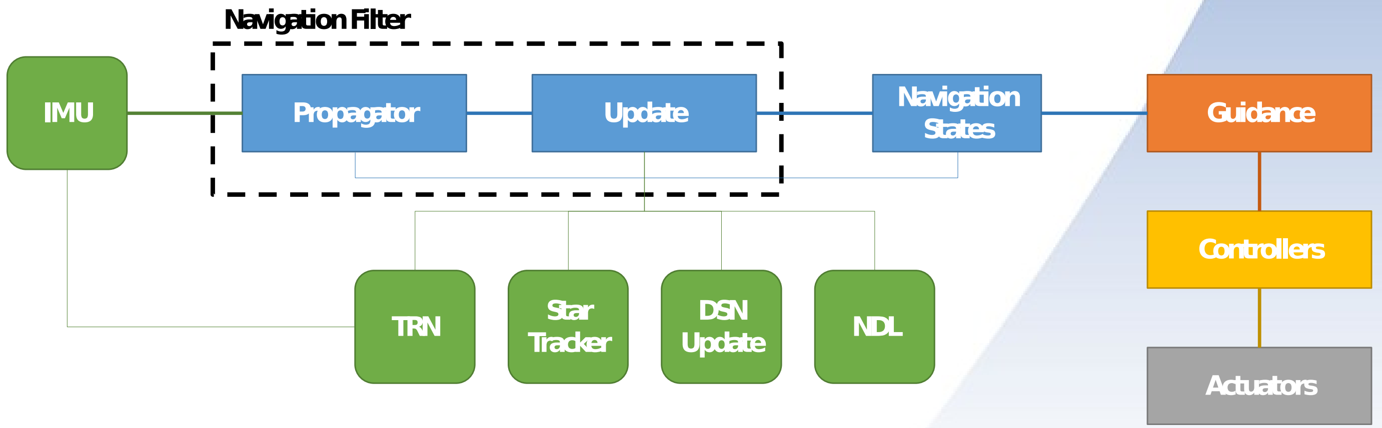
MATLA B

Navigation Performance Modeling Updates

AIAA 2022-0607

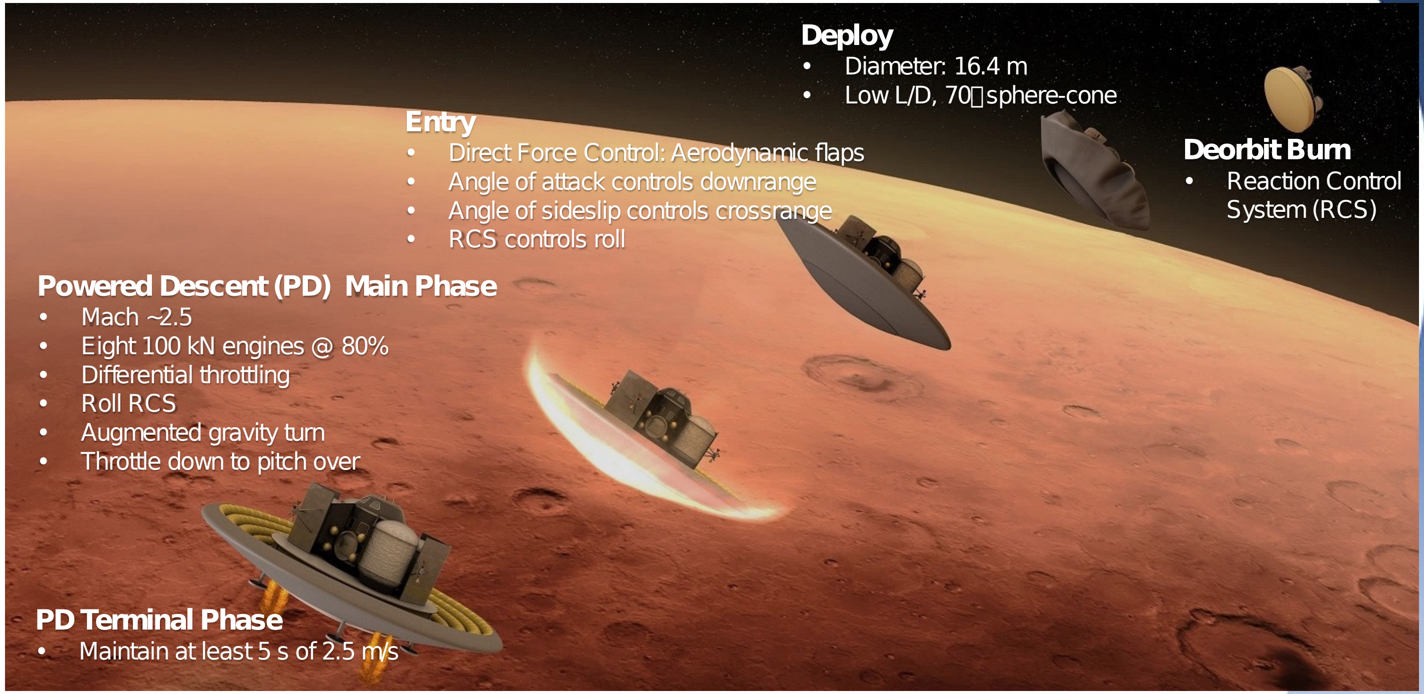
Safe & Precise Landing

- **Safe & precise crewed landing landings at the Moon and Mars will require evaluation of, and advances in, GN&C technologies**
- **Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) project assess these technologies and their performance effects**
  - Focus on deorbit/entry, descent, and landing (DDL/EDL)
  - 6DOF integrated performance simulations
  - Modeling of GN&C systems with varying levels of quality and fidelity
- **POST2-based simulation framework updated with navigation sensors running in-the-loop**
  - Used this framework to assess government reference human-scale Lunar and Mars lander and entry systems
  - Provides users with method of building detailed simulations with "off-the-shelf" models that can represent a variety of systems
  - Fast simulation run time (~10 min for 8000-sample Monte Carlo) enables quick turnaround of trade studies
  - AIAA 2022-0607, AIAA 2022-0609



Humans to Mars: NASA Reference EDL System

- **Low lift-to-drag (L/D) deployable decelerator**
  - Entry from 1 Sol polar orbit
  - ~50 t entry mass, 20 t payload
  - 16.4 m inflatable decelerator (HIAD)
  - Supersonic retropropulsion: 8x 100 kN @ 360 s Isp with differential throttling
- **Literature**
  - Architecture
    - Overview: AIAA 2016-5494
    - Phase 2 Summary: AIAA 2018-5190
    - Phase 3 Summary: AIAA 2020-1509
  - Vehicle Design
    - Deployable Decelerators: AIAA 2018-5191
    - Descent Systems: AIAA 2018-5193
    - HIAD Shape Morphing: AIAA 2020-1266
  - Simulation
    - Simulation Framework: AIAA 2020-0366
  - GN&C
    - Guidance Design: AAS 17-254, AIAA 2020-0846
    - Integrated Air Data System: AIAA 2019-0663
    - Navigation Requirements: AIAA 2019-0661
    - Navigation Performance: AIAA 2022-0607



	Loiter	Deorbit	Coast	Entry Interface	Entry	Powered Descent	Vertical Descent
Propulsion	RCS					Main Engines & RCS	
Guidance	Open-Loop				NPCG		
Steering Law	Attitude Hold				DFC	Augmented Gravity Turn	Vertical
Roll Control	RCS						
Pitch/Alpha, Yaw/Beta Control	RCS				Aerodynamic Flaps	Differential Throttling	
RCS Control Law	Phase-Plane						

Navigation Sensors

- **Inertial Measurement Unit (IMU)**
  - Generalized strapdown model
  - Scale factors, biases, internal misalignments, random walk/drift
- **Star Tracker**
  - Low-fidelity model (corrupted truth values)
- **Terrain-Relative Navigation (TRN) Camera**
  - Medium-fidelity model
  - Feature matching algorithm with state estimation
- **Navigational Doppler LIDAR (NDL)**
  - Tri-beam system (beams intersect terrain DEM)
  - Error model accounts for modulation period and bandwidth, beam wavelength, frequency, and pointing knowledge

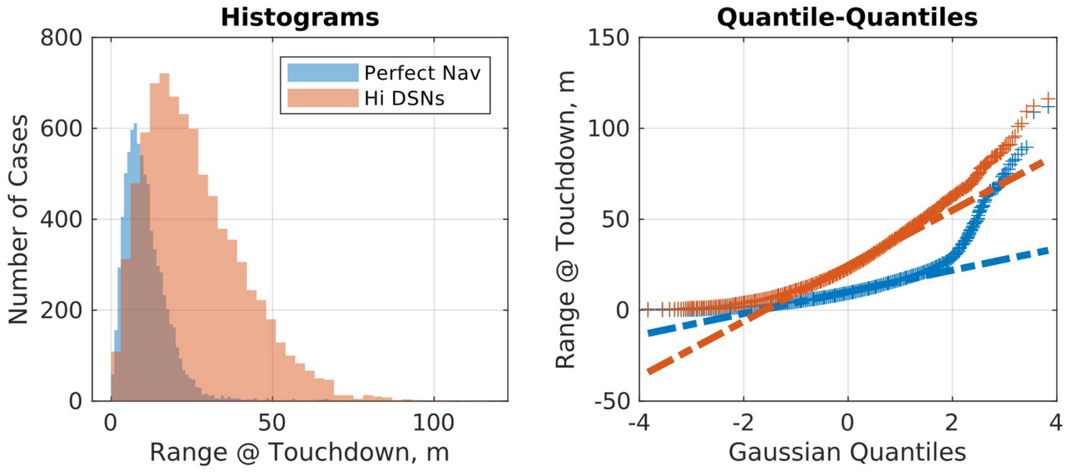
Loiter	Deorbit	Coast	Entry Interface	Entry	Powered Descent	Vertical Descent
IMU	IMU	IMU	IMU	IMU	IMU	IMU
Star Tracker		Star Tracker				
DSN		DSN				
				TRN	TRN	
					NDL	

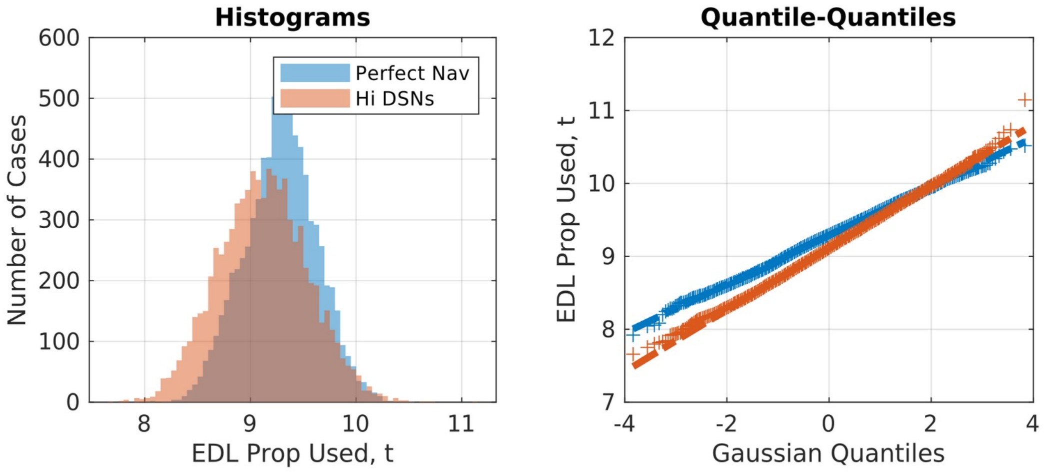
Performance Trades

- Investigated performance impacts of radio navigation and ground-relative sensor trades

Category	Trade ID	Trade	Plot Label	DSN (Pre-DOI)	DSN (Pre-EI)	TRN	NDL
Baseline	1	Perfect Navigation	Perfect Nav	None	None	None	None
	2	High DSN Updates	Hi DSNs	High	High	High	Yes
DSN Trades	3	Single DSN Update	Single DSN	High	None	High	Yes
	4	Medium DSN Updates	Med DSN	Medium	Medium	High	Yes
	5	Ultra DSN Updates	Ult DSN	Ultra	Ultra	High	Yes
	6	Low 2nd DSN Update	Low 2nd DSN	High	Low	High	Yes
Ground-Relative Sensor Trades	7	Medium TRN	Med TRN	High	High	Medium	Yes
	8	Medium TRN, No NDL	Med TRN No NDL	High	High	Medium	None
	9	Low TRN	Low TRN	High	High	Low	Yes
	10	Low TRN, No NDL	Low TRN No NDL	High	High	Low	None

Baseline Results

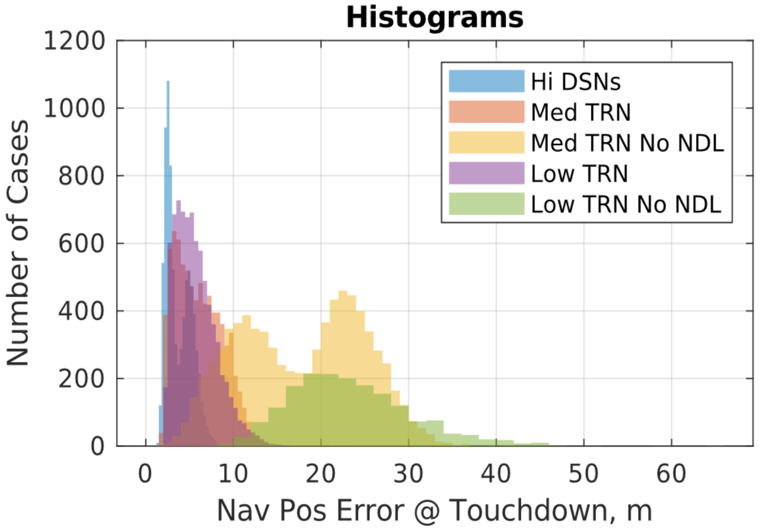


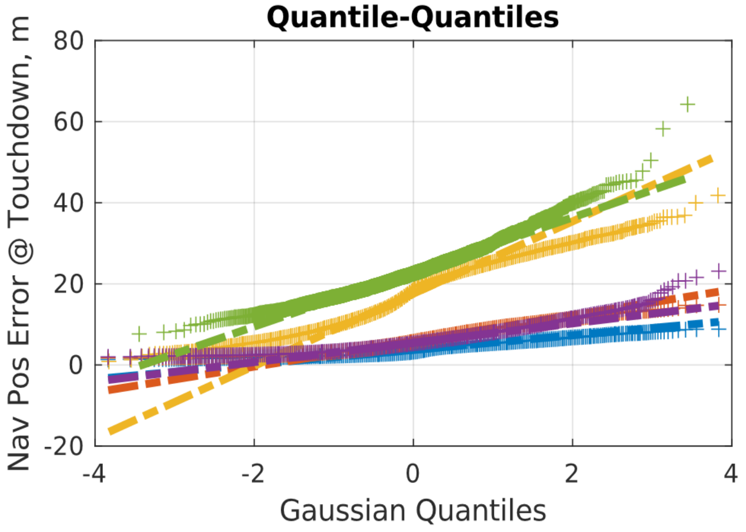


	Perfect Nav	Hi DSNs
Nominal	6.33	1.41
Mean	11.06	25.78
3-sigma	24.15	46.01
1.00 %-tile	1.11	2.55
99.00 %-tile	42.67	68.92
Max Value	111.89	116.22
Min Value	0.09	0.68
Success	7999	7997
Percent	100	100

	Perfect Nav	Hi DSNs
Nominal	9.8	9.65
Mean	9.29	9.12
3-sigma	1.02	1.26
1.00 %-tile	8.51	8.19
99.00 %-tile	10.06	10.1
Max Value	10.52	11.15
Min Value	7.92	7.66
Success	7999	7997
Percent	100	100

Ground-Relative Sensor Quality Trades





	Hi DSNs	Med TRN	Med TRN No NDL	Low TRN	Low TRN No NDL
Nominal	4.67	5.08	21.22	4.25	14.97
Mean	3.74	6.05	17.79	5.72	23.41
3-sigma	4.34	7.86	21.38	7.12	20.72
1.00 %-tile	1.73	2.11	4.57	2.38	11.48
99.00 %-tile	7.23	12.17	31.78	12.73	42.51
Max Value	8.83	14.8	41.83	23.14	64.26
Min Value	1.36	1.71	0.89	2	7.65
Success	7997	7997	7709	7998	1756
Percent	100	100	96.4	100	22

- **First case is baseline**
  - Because each sample is an integrated trajectory, can evaluate success rate
- **NDL sensor (late in EDL phase) “cleans up” TRN errors**
- **A high-enough quality TRN sensor and no NDL may be able to meet requirements, but at the cost of success rate**
  - Could a high-altitude TRN buy back performance from DSN?

Category	Trade ID	Trade	Plot Label	DSN (Pre-DOI)	DSN (Pre-EI)	TRN	NDL
Baseline	1	Perfect Navigation	Perfect Nav	None	None	None	None
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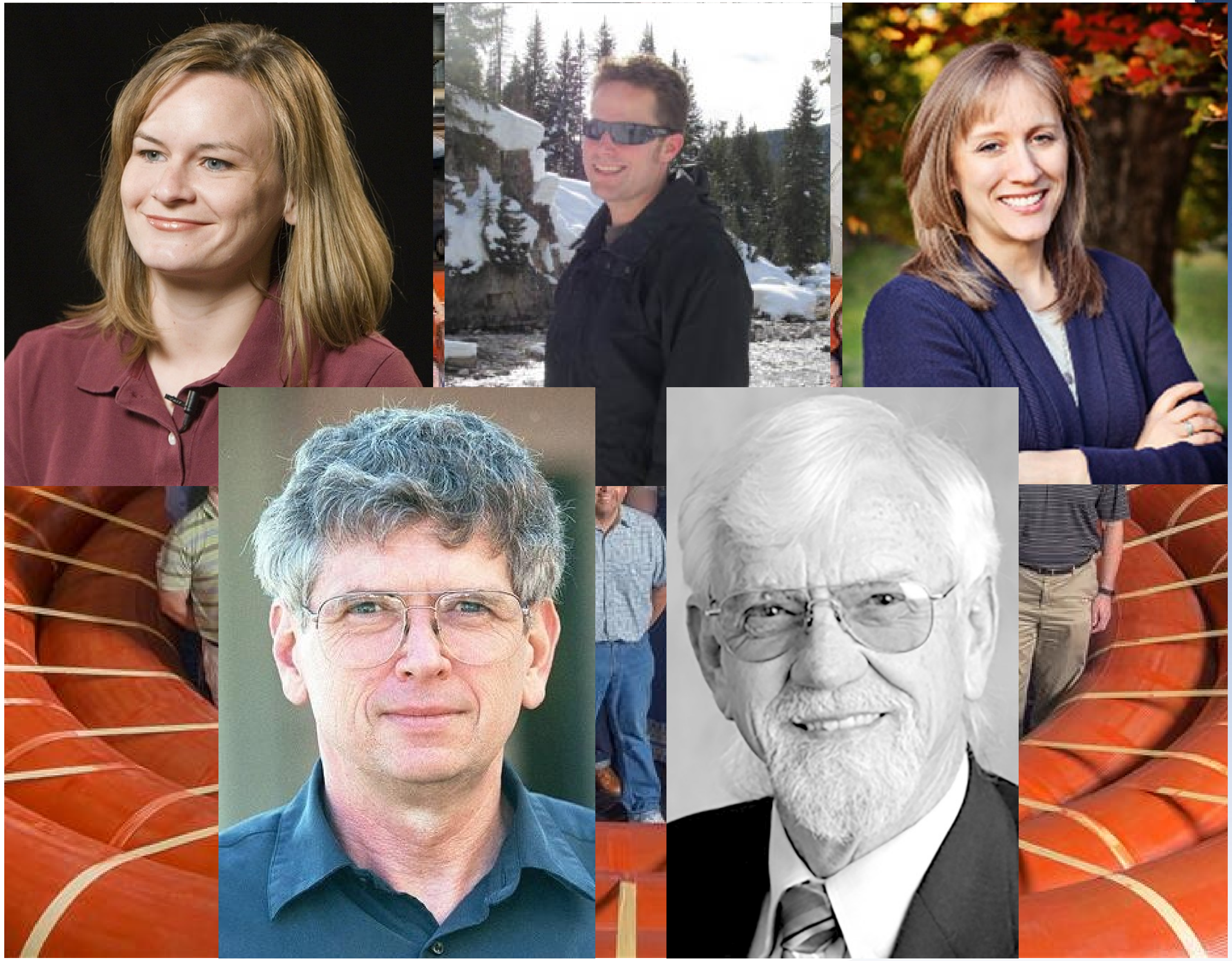
Ground-Relative Sensor Trades	7	Medium TRN	Med TRN	High	High	Medium	Yes
	8	Medium TRN, No NDL	Med TRN No NDL	High	High	Medium	None
	9	Low TRN	Low TRN	High	High	Low	Yes
	10	Low TRN, No NDL	Low TRN No NDL	High	High	Low	None

Summary & Future Work

- **Flight mechanics modeling & simulation covers a wide variety of disciplines**
  - Experience has shown that treating flight systems in an end-to-end, integrated sense can provide enhanced insight into flight mechanics performance
  - POST2 is an example of a flight-validated flight mechanics modeling & simulation tool that can benefit from changes to programming and computer hardware paradigms
- **POST2 codebase updates**
  - Modified to be thread-safe, enabling faster internal trajectory optimization via parallel calculations
  - Also enables the creation of an API, permitting POST2 to be used as dynamics driver within other applications
- **Navigation performance modeling updates**
  - Generalized navigation sensor models implemented into POST2 sim framework
  - Enables fast analysis of closed-loop GN&C (nav-in-the-loop) integrated performance for a variety of flight systems
- **Future Work**
  - The road to POST3 – What will it look like?
  - Confident that the “Developers-as-Users” vertical integration model is the standard to maintain

Acknowledgements

- **D205 & D205 Management**
  - Ron Merski & Monica Hughes
- **POST2 Development Team & Support Team**
- **Jill Prince**
- **Jeremy Shidner**
- **Alicia Dwyer-Cianciolo**
- **Richard Powell (ret.)**
- **Robert Tolson (ret.)**

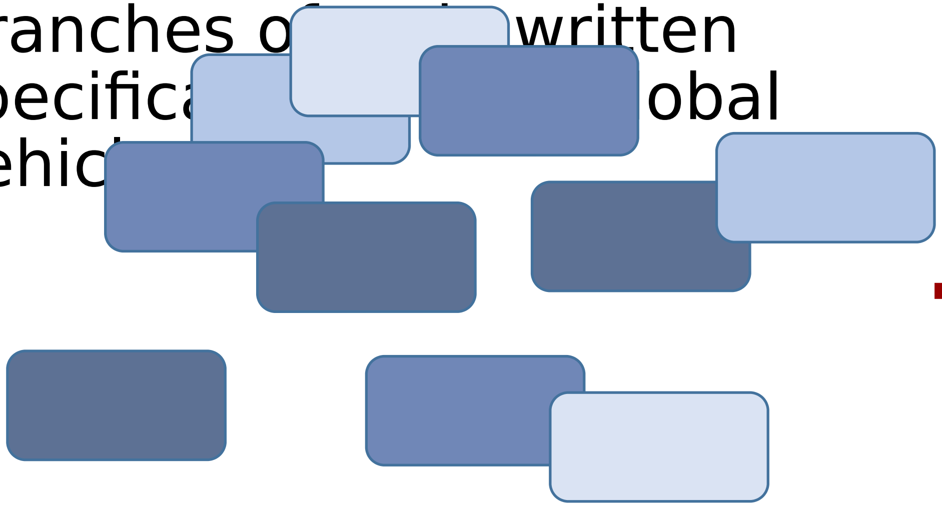


Backup

Memory Restructuring

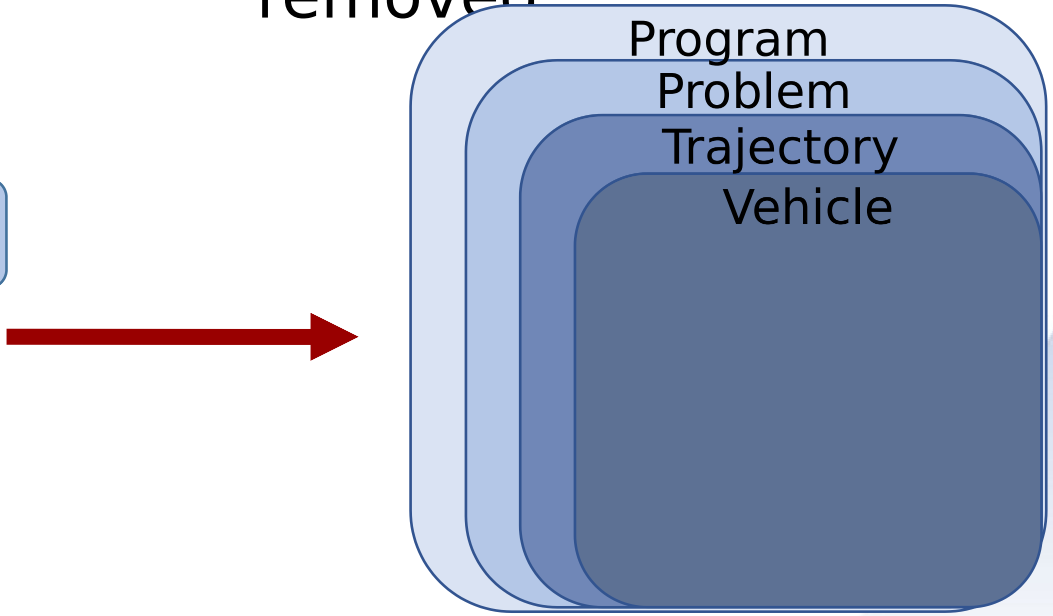
Before Thread-Safe Changes

- Many global memory structures, remnants of Fortran common blocks
- No grouping within global structures
- Branches o written specifica obal vehic



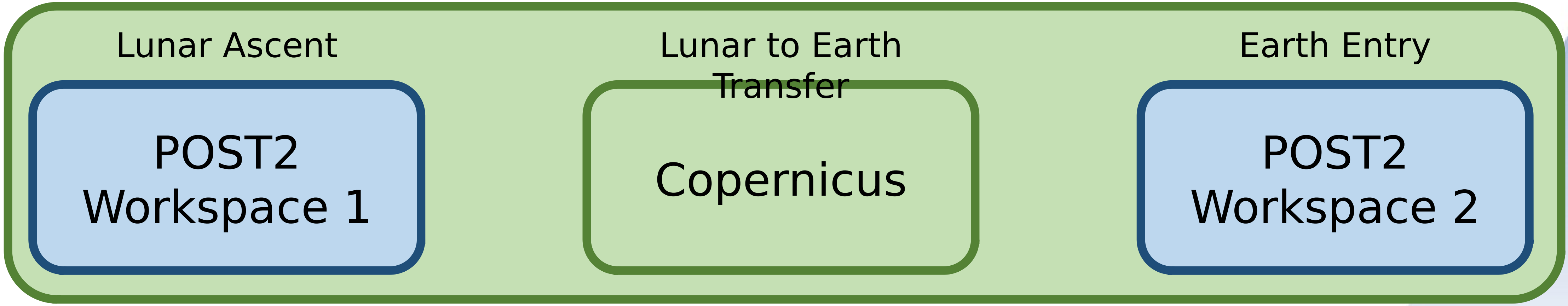
After Thread-Safe Changes

- Global memory space restructured into hierarchy based on instruction execution
- All vehicle-specific logic removed



Workspace Structuring

- More recent updates to the API introduced the concept of “workspaces”
- Each POST2 workspace is an encapsulated set of inputs (usually defined by an input deck)
- Permits the same POST2 instantiation to run multiple workspaces either in sequence or in parallel

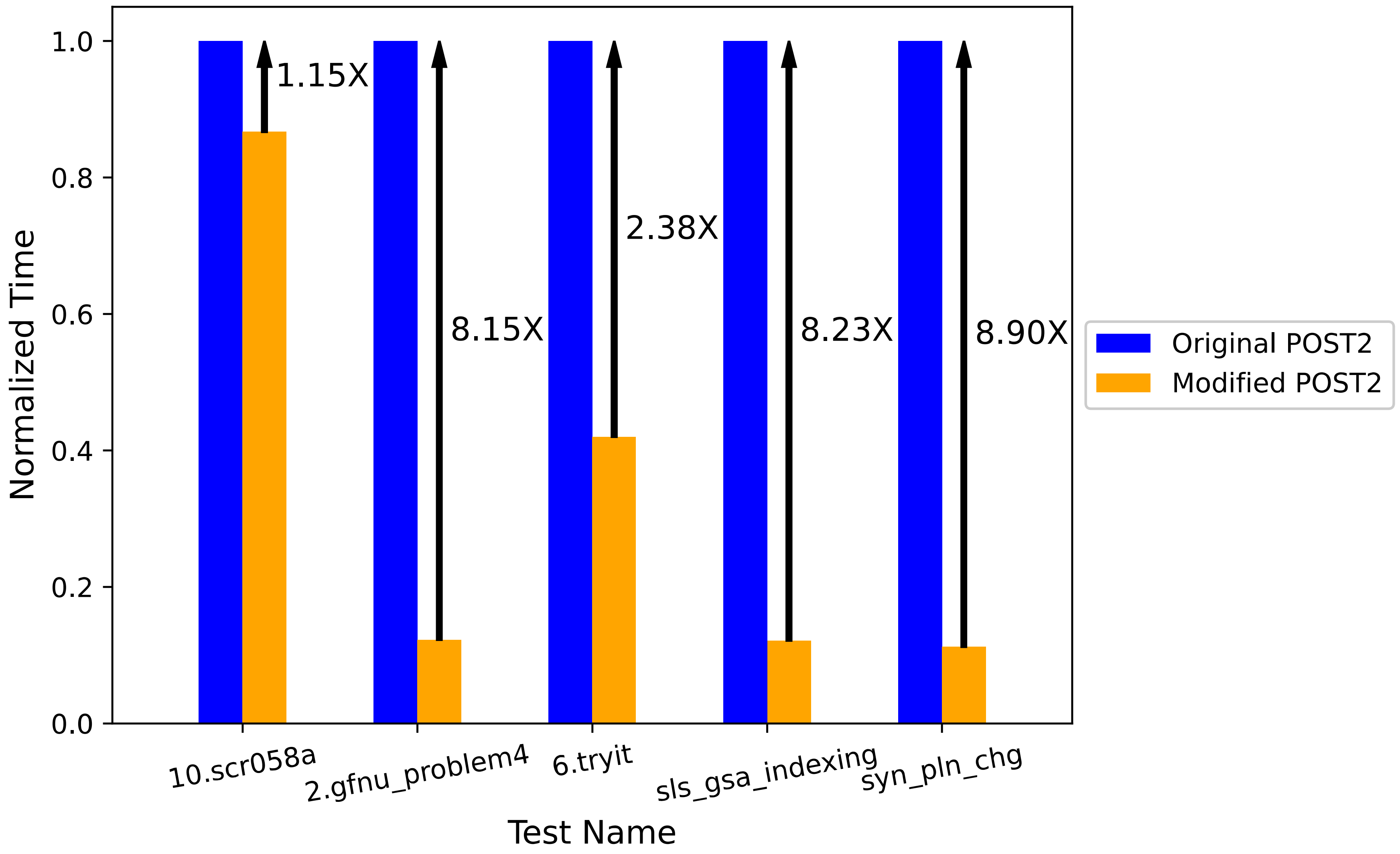


API Example: Copernicus

- **Set of POST2 functions are compiled into a callable Python module via CFFI package**
- **JSON plugins are developed specific to Copernicus input decks (idecks) which handle inputs and outputs being passed to and from POST2**
- **Python script is called by this plugin to interface with POST2**
  - Runs within same Python process as Copernicus
  - Upon loading the plugin, the designated POST2 input deck is loaded into memory; only occurs a single time (only true I/O in this process)
  - At this point, each time Copernicus makes a call to propagate:
    - Inputs from JSON plugin are passed through Python module to POST2, then input deck is executed with updated inputs from Copernicus (**does not alter input deck file**)
    - Outputs from POST2 are passed back through Python module (**as a data stream in memory, not through I/O**) to JSON plugin/Copernicus

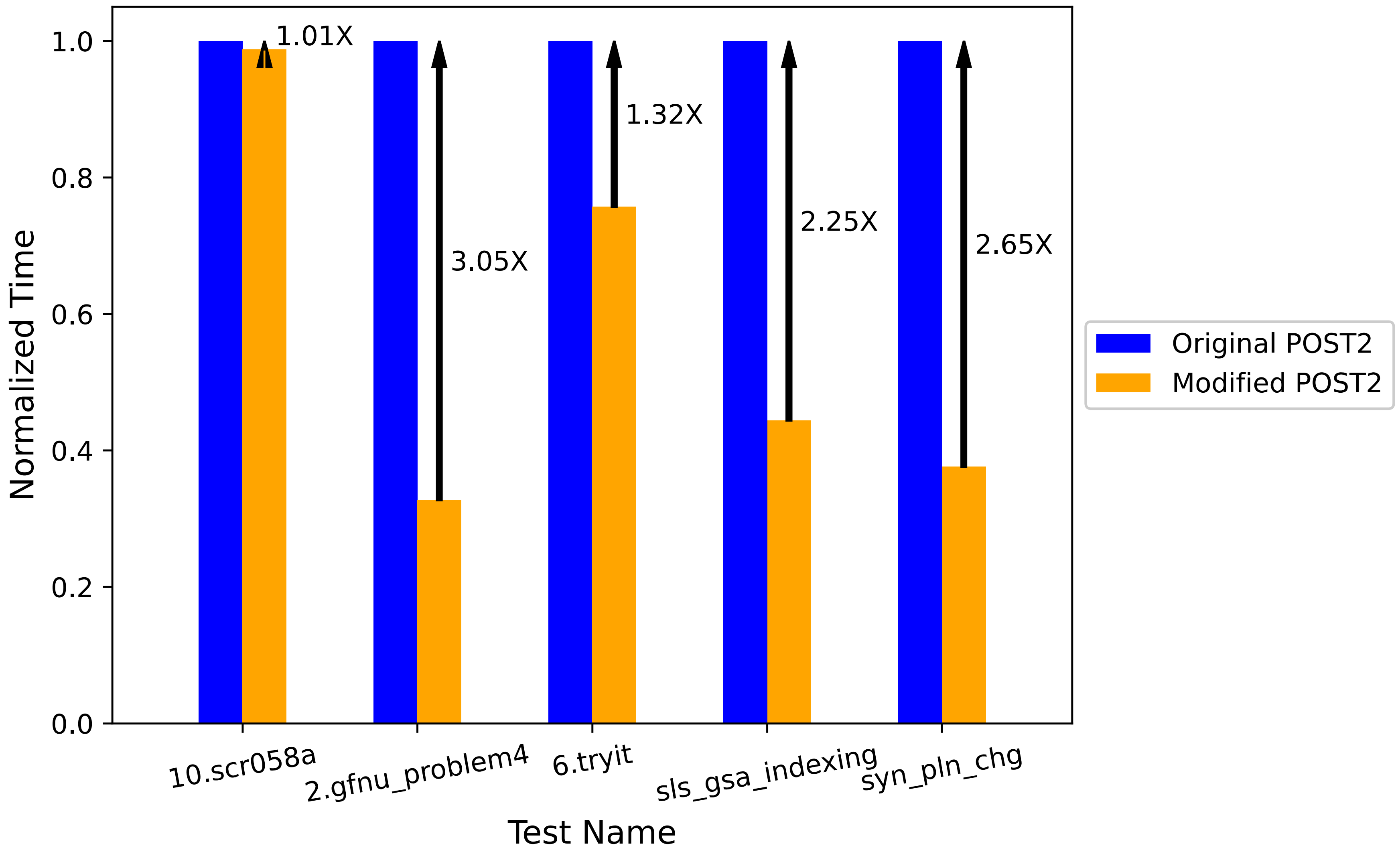
Regression Tests Gradient Calculations

Lower is Better



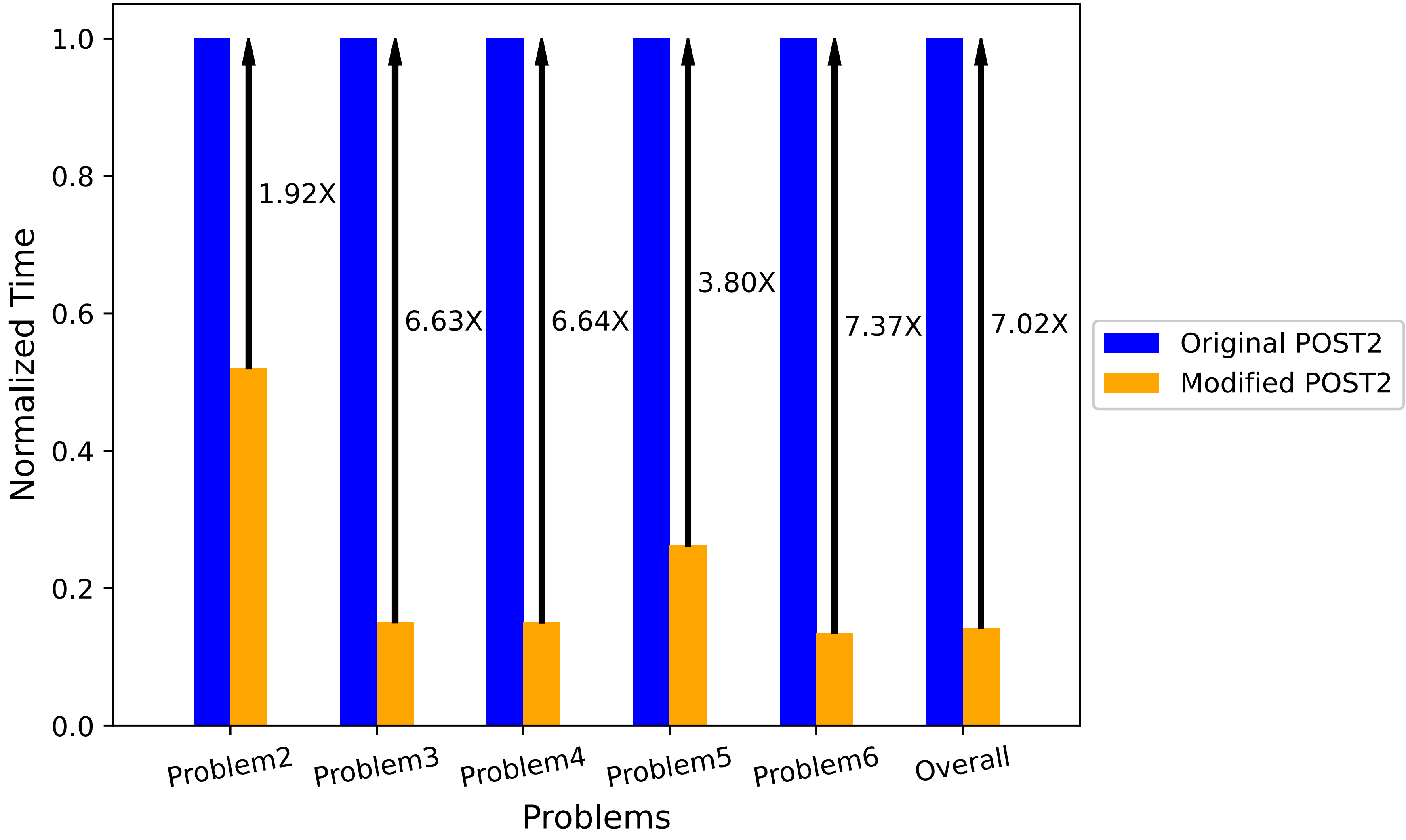
Regression Tests Overall Time

Lower is Better



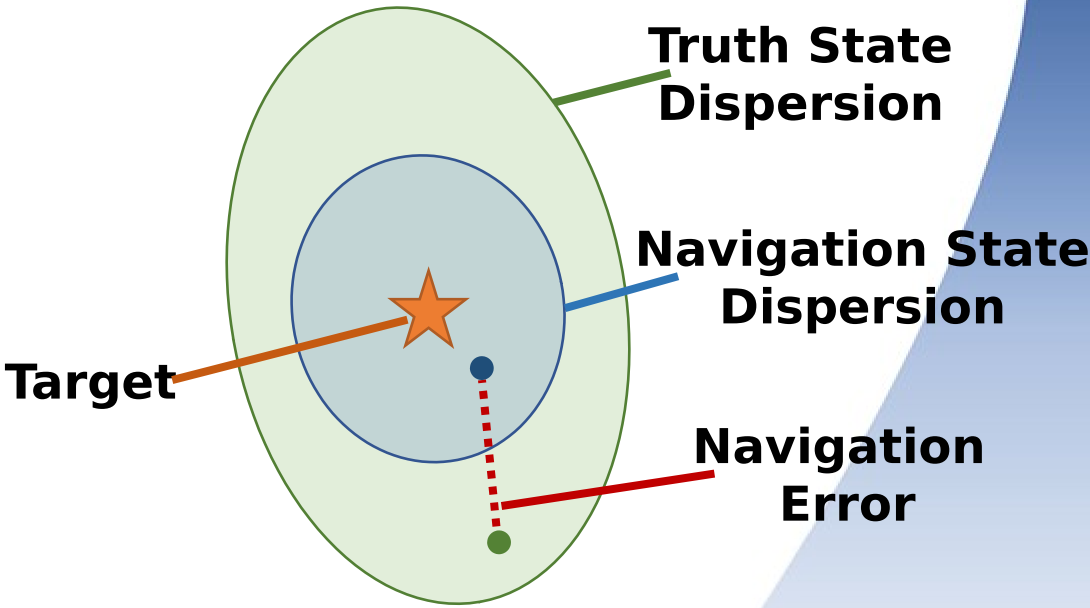
Lunar Lander Gradient Calculations

Lower is Better

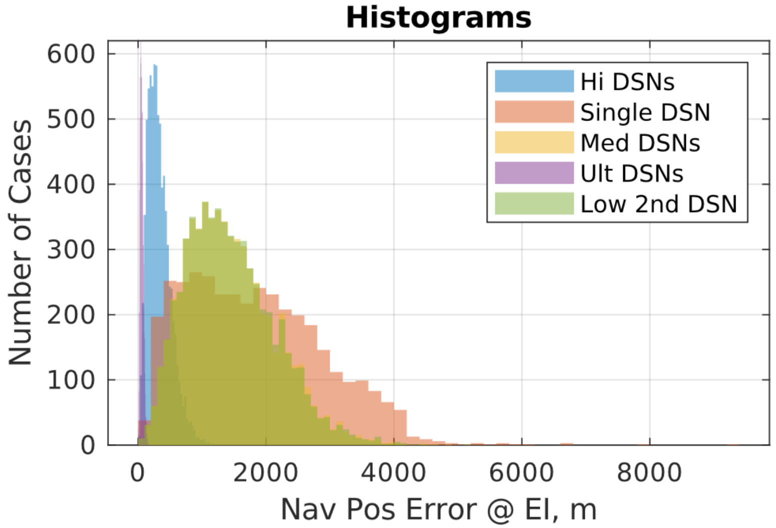


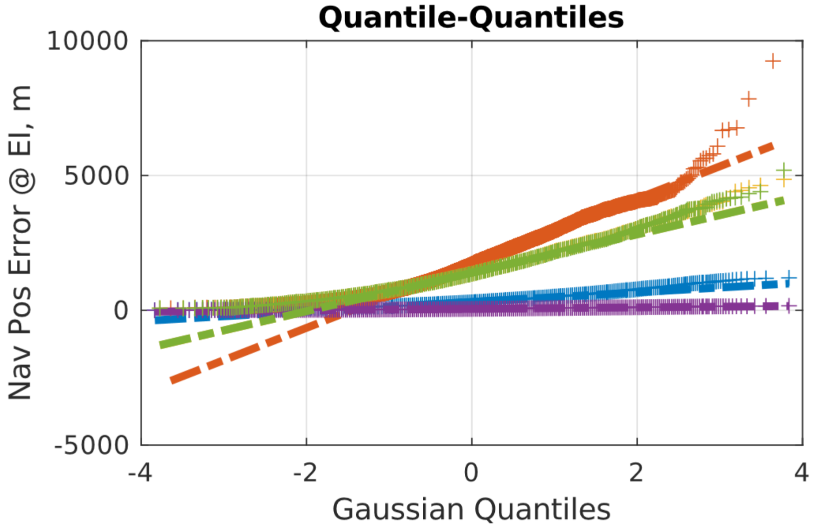
Performance Metrics

- **Navigation error**
  - Describes overall behavior of navigation system
- **Landing precision**
  - Describes how well integrated vehicle lands near pre-designated target
  - 50 m range or better in a 3σ sense is desired (99%-tile statistics also assessed)
- **Success rate**
  - Describes percentage of 8,000 Monte Carlo samples that achieve a safe landing:
    - Horizontal velocity of less than or equal to 1.0 m/s
    - Vertical velocity of less than 3.0 m/s
    - Angle off vertical of less than 3°
    - Max angular rate about any axis of less than 0.5°/s
  - Success rate of 99% or better is desired



Deep Space Network Quality Trades





	Hi DSNs	Single DSN	Med DSNs	Ult DSNs	Low 2nd DSN
Nominal	211.69	334.18	1234.96	31.56	1234.97
Mean	330.82	1827.88	1447.81	56.96	1442.67
3-sigma	544.56	3232.18	2101.72	77.19	2086.8
1.00 %-tile	50.17	196.33	234.01	14.13	234.19
99.00 %-tile	878.13	4344.25	3380.41	127.15	3378.17
Max Value	1206.09	9248.73	4857.03	166.5	5197.16
Min Value	4.64	78.7	78.82	2.92	78.66
Success	7997	3706	6242	7997	6237
Percent	100	46.3	78	100	78

- **First case is baseline**
- **2nd DSN Update prior to EI is critical**
  - Navigated position error is very sensitive to the final update (follows intuition)
- **Because each sample is an integrated trajectory, can evaluate success rate**

Category	Trade ID	Trade	Plot Label	DSN (Pre-DOI)	DSN (Pre-EI)	TRN	NDL
Baseline	1	Perfect Navigation	Perfect Nav	None	None	None	None
	2	High DSN Updates	Hi DSNs	High	High	High	Yes
DSN Trades	3	Single DSN Update	Single DSN	High	None	High	Yes
	4	Medium DSN Updates	Med DSN	Medium	Medium	High	Yes
	5	Ultra DSN Updates	Ult DSN	Ultra	Ultra	High	Yes
	6	Low 2nd DSN Update	Low 2nd DSN	High	Low	High	Yes

Navigation Performance Summary

	Trade	Success Rate %	Landing Precision 99%-tile, m	EDL Prop Used 99%-tile, t	Nav Pos Err @ TD 99%-tile, m	Nav Vel Err @ TD 99%-tile, m/s	Nav Att Err @ TD 3σ, deg
Baseline	Perfect Navigation	100.0	42.67	10.06	0.00	0.00	0.00
	High DSN Updates	100.0	68.92	10.10	7.23	0.15	0.21
DSN Trades	Single DSN Update	46.3	1871.56	10.11	11.49	0.22	0.27
	Medium DSN Updates	78.0	982.88	12.88	12.26	0.28	0.78
	Ultra DSN Updates	100.0	48.45	9.93	7.04	0.16	0.19
	Low 2nd DSN Update	78.0	938.60	12.70	12.10	0.28	0.63
Ground-Relative Sensor	Medium TRN	100.0	70.25	10.10	12.17	0.16	0.22
	Medium TRN, No NDL	96.4	67.54	10.19	31.78	1.02	0.03
	Low TRN	100.0	72.44	10.10	12.73	0.16	0.22